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ABSTRACT

A new time domain phase comparator is described. The device uses a novel technique to allow time domain phase measurements to be made with period and time interval counters without the use of offset reference oscillators. The device uses a single reference oscillator and allows measurements with a phase resolution greater than the noise floor of the reference. Data is presented showing a phase resolution of 0.02ps at 5 MHz with a crystal reference. The device has application in measuring the phase stability of systems where approximate phase quadrature can be maintained.

INTRODUCTION

Ideally, a frequency distribution system should not contribute any noise to the frequency being distributed. Practically, this means that the elements of a frequency distribution system should introduce negligible phase noise compared to the phase noise of the reference oscillator. To ensure this in the most precise frequency distribution systems, one must be able to measure phase noise with a resolution greater than that available from the best reference oscillators. This means that one must use a phase noise measurement technique which cancels out the phase noise of the reference oscillator.

A well known simple system which accomplishes this is shown in Figure 1. The system is based on a low noise mixer and a 90° splitter to produce a voltage proportional to the phase difference between the RF voltages at the mixer input ports. By placing one or more test devices in the R. F. signal paths, the phase stability of the test devices can be measured by analyzing the voltage out of the mixer. Because the RF source is common to both legs of the system, its phase noise does not effect the output voltage. Figure 2 shows the spectral domain phase noise resolution of such a system at 5 MHz using a Shotky diode mixer. A lock-in amplifier was used as the noise analyzer.

It is in trying to apply this simple system to time domain noise analysis that a problem occurs. The time domain measures of phase stability [1,2], x(t) and y(t), require instantaneous measurements of the phase of a signal at periodic intervals. This is usually accomplished by superimposing the voltage carrying phase information on a low frequency beat, measuring y(t) with a period counter, and measuring x(t) with a time interval counter. Figure 3 outlines these techniques. In order to produce a beat with the simple system shown in Figure 1, two reference oscillators must be used. This, however, reintroduces the phase noise of the reference oscillators into the output. To cancel the reference oscillator contributions one must use two such systems in a dual mixer phase comparator [3], and use a time interval counter to measure the difference in the zero crossings of the two beats.

A SIMPLE TIME DOMAIN PHASE COMPARATOR

Though the dual mixer system works quite well, it requires double the circuitry as the simple system, and requires two reference oscillators one of which must be offset in frequency. One can make high resolution time domain phase stability measurements, however, with only a single reference if one realizes that the low-frequency modulation which enables counters to be used need not come from a beat between two oscillators. As shown in Figure 4, the purpose of the beat is just to accomplish voltage to time conversion so that a period or time interval counter can measure the voltage changes which correspond to phase changes. The beat can, thus, be any stable low frequency voltage modulation which is added to the mixer output. Figure 5 shows a block diagram of such a time domain comparator based on the simple measurement system.

A convenient way to obtain a stable enough low frequency modulation is to divide down a reference oscillator output and smooth the resulting square wave with a low pass filter. Figure 6 shows the partial schematic of a time domain phase comparator using this method of obtaining the modulation. The amplifier after the mixer defines the bandwidth of the phase noise and amplifies the mixer output so the noise of the modulating voltage does not reduce the phase resolution of the comparator.

The line stretcher provides a convenient means of calibrating the system. The counter is set to time interval, and the change in time interval, Δt, is recorded as a function of the change in line stretcher length, ΔL. The system calibration is then given by:

$$x = (c\,K)^{-1}\,\Delta t \quad \text{(Time interval)}$$

$$y = (c\,K)^{-1}\,\frac{\Delta T}{T} \quad \text{(period)}$$

where:

$$x = \frac{\Delta\phi}{2\pi f}$$

$$y = \frac{\delta f}{f}$$

$$K = \frac{\Delta t}{\Delta L}$$

and where T is the period of the modulation. Typically in the system built, at 5 MHz, $(c\,K)^{-1}$ has been about 10^{-8} so a counter resolution of 10^{-7}s will yield a phase resolution (x) of 10^{-15}s.

The simple series L and C phase shifters shown in Figure 6 were found to be quite stable. The capacitor was NPO and the inductor was ferrite core. The inductor is adjusted while monitoring the mixer output to produce phase quadrature.

RESULTS

Figures 7, 8, 9, and 10 show detailed schematics of the time domain phase comparator outlined in Figure 6. As in all ultra low noise work, care must be exercised in keeping 60 Hz interference as low as possible. In this comparitor, this was accomplished by the use of a built in voltage regulator and magnetic shielding; the whole device, the diode mixer and the inductor in the phase shifter was shielded with Co-Netic foil. The comparator is designed to use an externally supplied 10 Hz square wave for modulation. The noise bandwidth, $(4\,RC)^{-1}$, is 16.7 Hz. Both the beat frequency and the noise bandwidth can be changed by changing the appropriate RC time constant. To ensure good results the comparator has its own level sensing trigger. The monitor output is a linear output which aids in adjusting the phase splitter. Both a TTL and a

pulse output are supplied for the counter. For short lines, the TTL output yielded somewhat better results. The pulse output is floating for ground loop isolation.

The device's noise resolution was measured using a Hewlett Packard 5245 counter as the 10 Hz source, an oscilloquartz B5400 5 MHz crystal oscillator as the reference, and a Hewlett-Packard 5345 counter as the time interval/period counter. Figures 11 and 12 show the results for time interval and period respectively. Figure 11 shows $\sigma_{TX}(\tau)$ verses averaging time, τ. σ_{TX} is defined by:

$$\sigma^2_{TX}(\tau) = \frac{1}{2}\left\langle [x(t+\tau) - x(t)]^2 \right\rangle$$

It is a measure of clock error similar to $U_x(\tau)$ used in clock modeling[4], but normalized to measure single point error. Figure 12 shows the two sample Allan Variance, $\sigma_y(\tau)$, verses averaging time. The variance is not strictly the zero dead time variance; for $\tau = 0.1s$, $T = 2\tau$, and for $\tau \geq 1s$, $T \simeq \tau$.

Notice the device's phase noise is approximately 0.02ps over the range measured. This compares quite favorably with the NBS dual mixer system[3].

CONCLUSIONS

The simple time domain phase comparator discussed in this paper offers a means of making ultra high resolution phase stability measurements with a minimum of equipment. Though not as versatile as the dual mixer comparator, in applications where approximate phase quadrature can be maintained, the simple time domain phase comparator will yield as good or better results.

ACKNOWLEDGEMENTS

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1. J. A. Barnes, et al., "Characterization of Frequency Stability," IEEE Trans. IM-20, p. 105 (1971).

2. B. E. Blair, ed., Time and Frequency: Theory and Fundamentals, NBS Monograph 140, CODEN: NBSMA6, U. S. Superintendent of Documents, Catalogue #C13.44:140, Ch. 8 (1974).

3. D. W. Allan and H. Daams, "Picosecond Time Difference Measurement System" 29th Annual Symposium of Frequency Control (Atlantic City, 1975).

4. B. E. Blair, op. cit, Ch. 9.

FIGURES

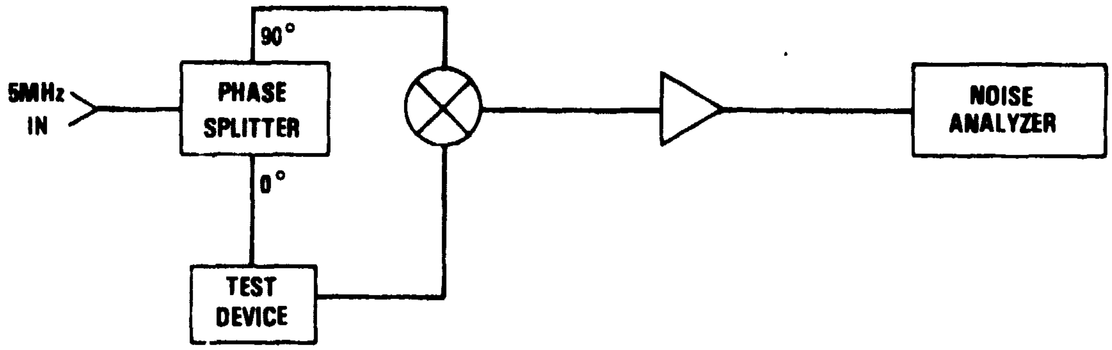


Fig. 1–A simple phase noise measurement system

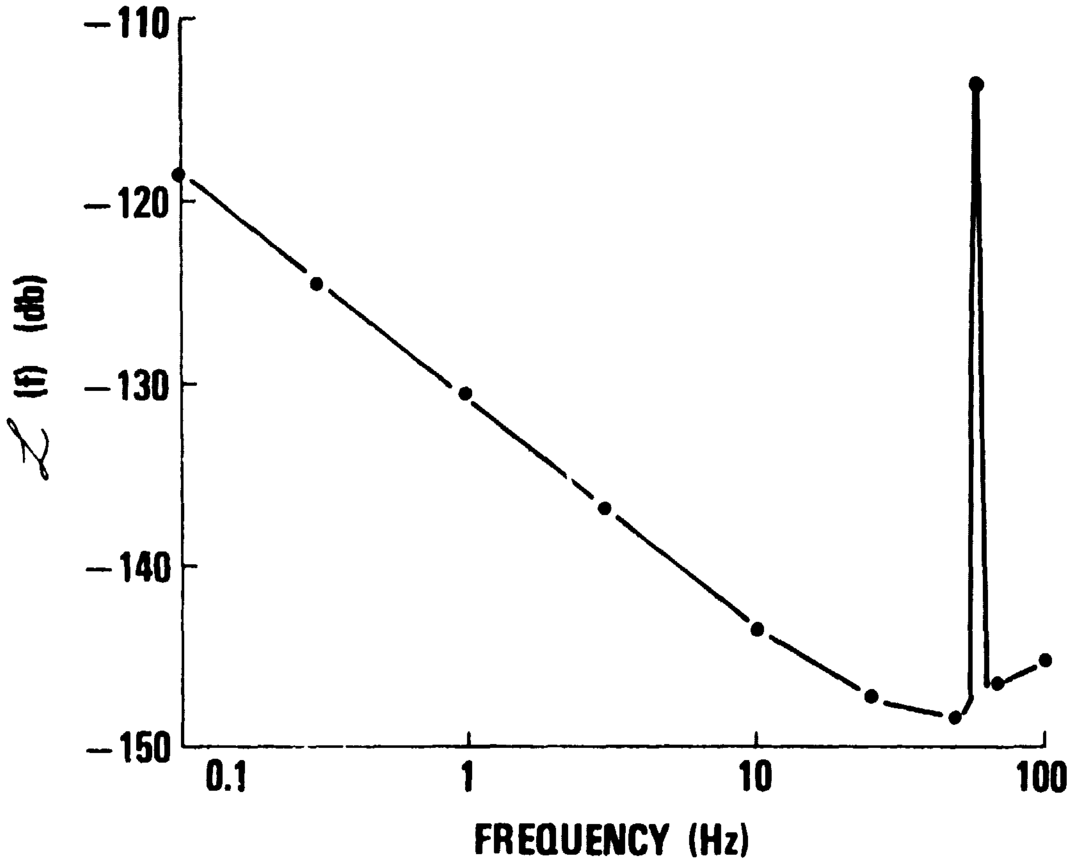


Fig. 2–Diode Mixer Phase Noise

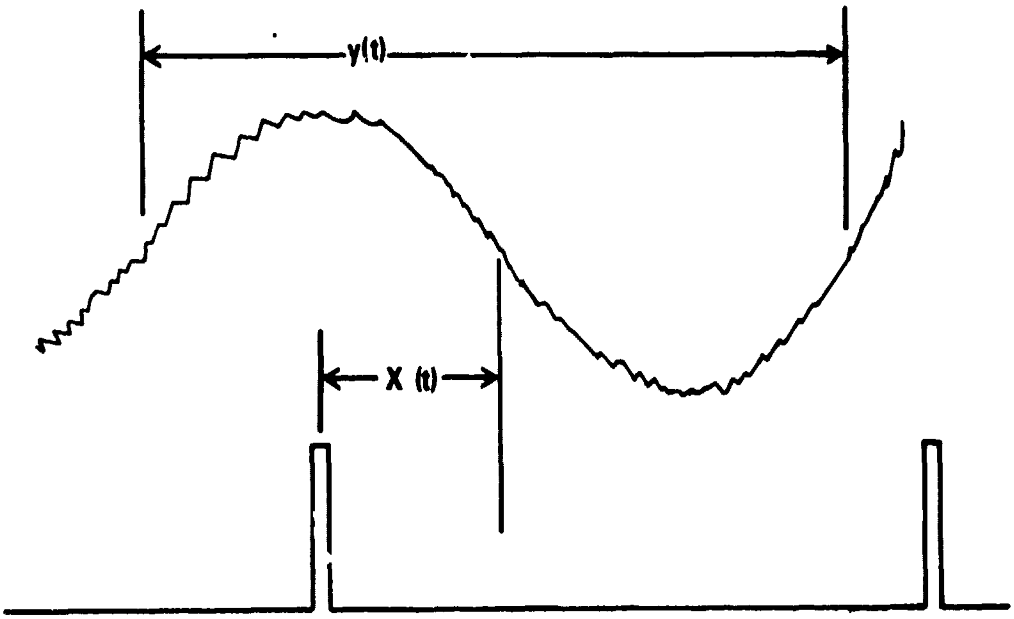


Fig. 3—Measuring x(t) and y(t)

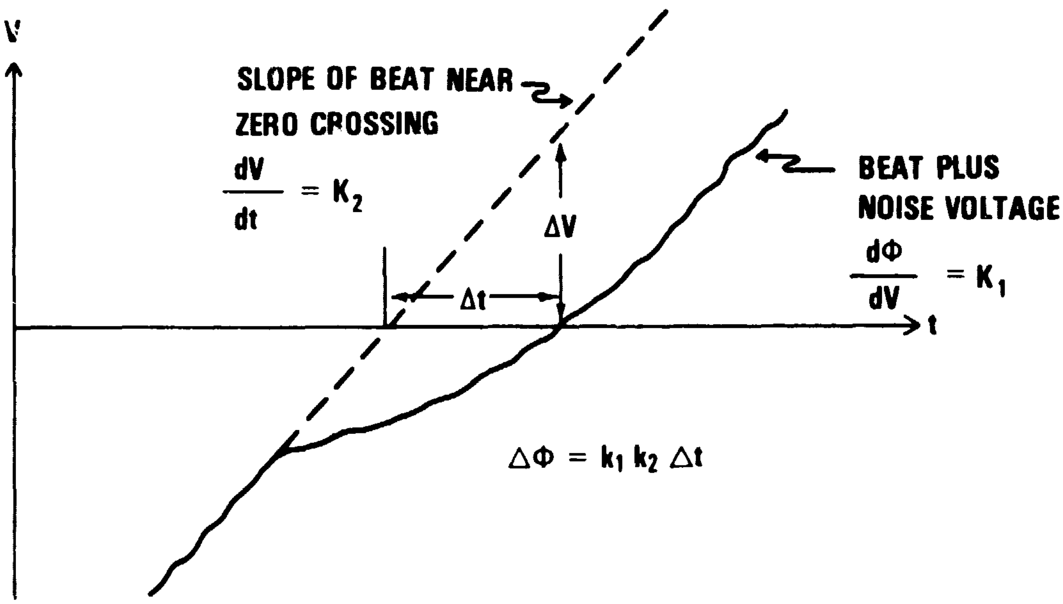


Fig. 4—Voltage to tune conversion by low frequency beat

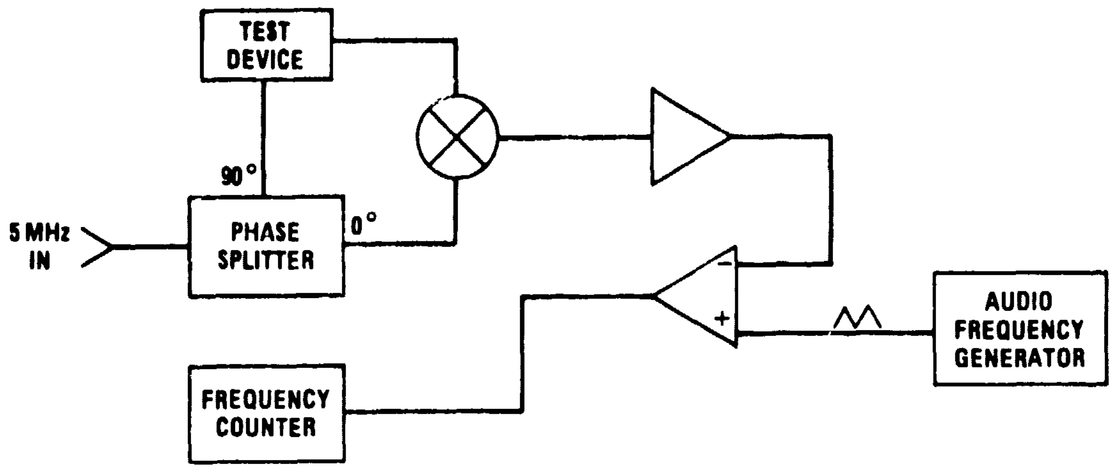


Fig. 5–Time Domain Measurement System

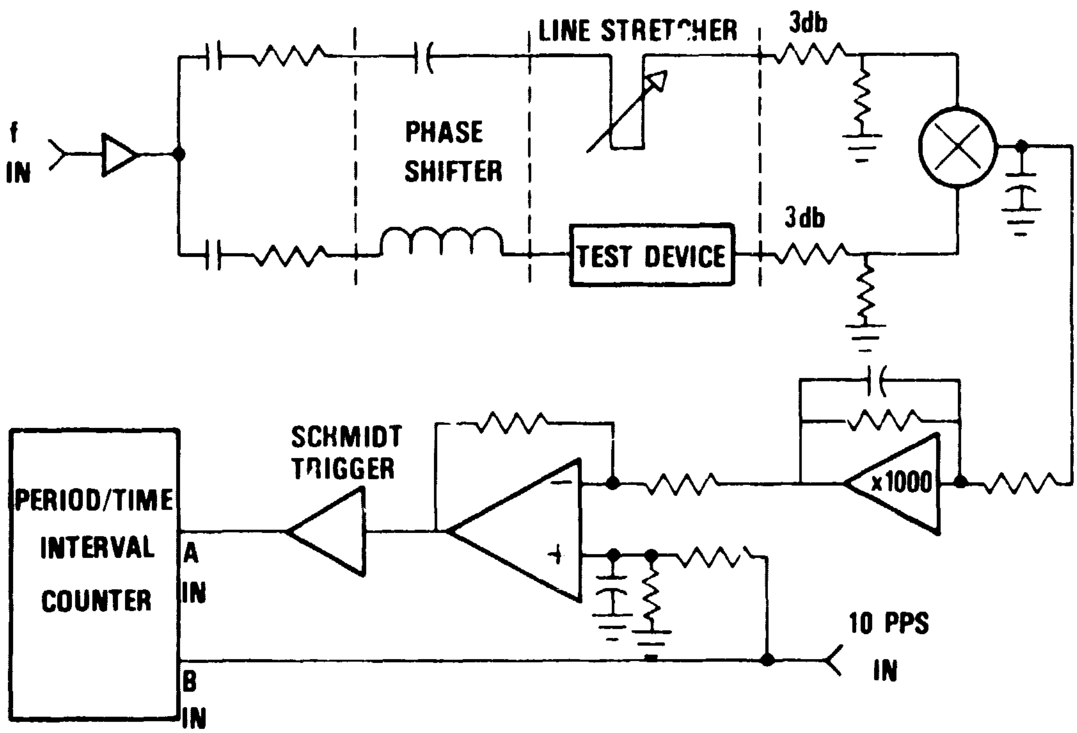


Fig. 6–Time Domain Phase Comparator

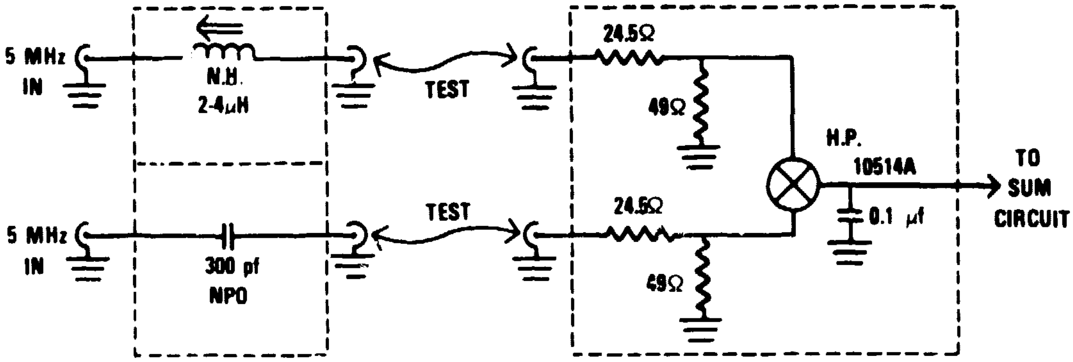


Fig. 7—Phase Comparator Schematic - Phase Shifter - Mixer

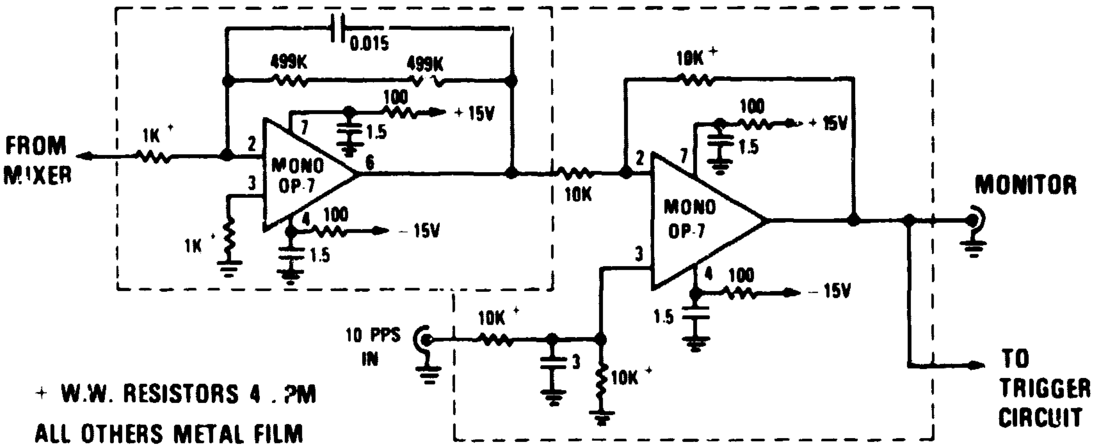
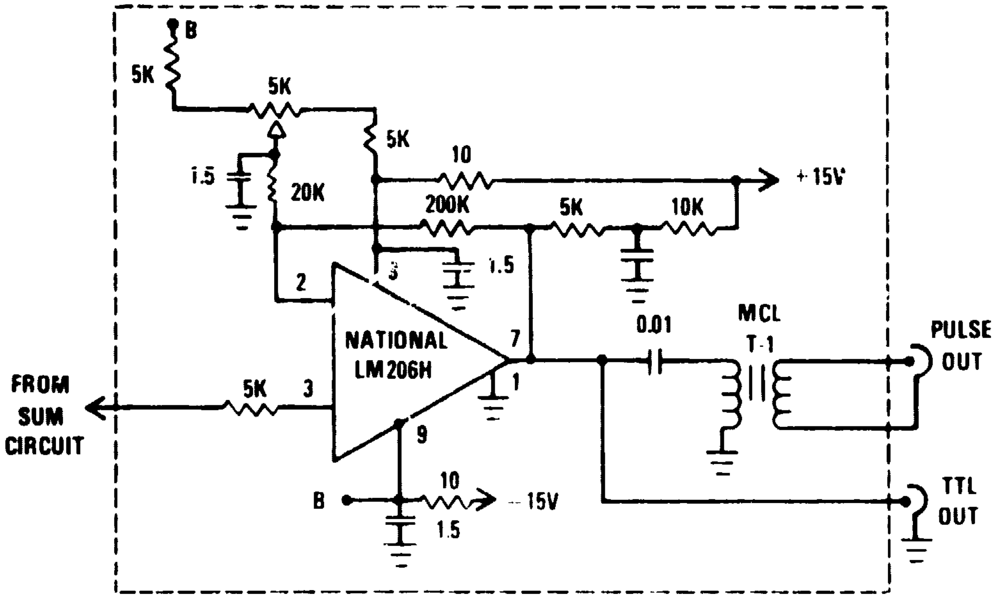


Fig. 8—Phase Comparator Schematic - Sum Circuit



ALL RESISTORS METAL FILM

Fig. 9—Phase Comparator Schematic - Trigger Circuit

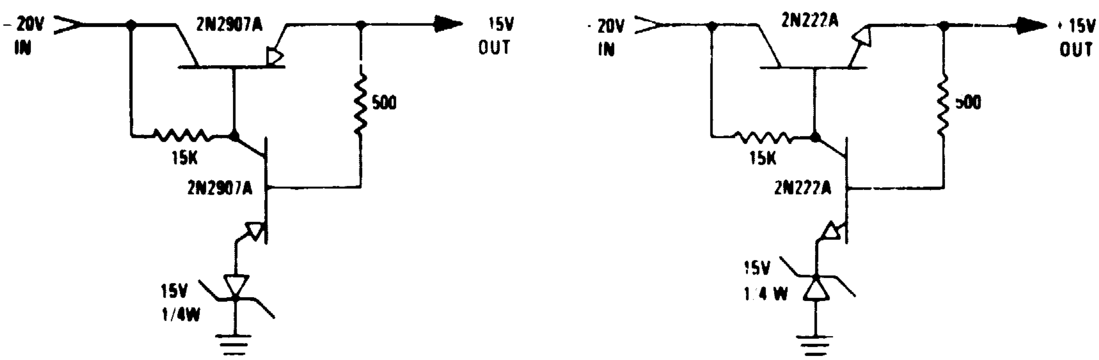


Fig. 10—Phase Comparator Schematic - Voltage Regulator

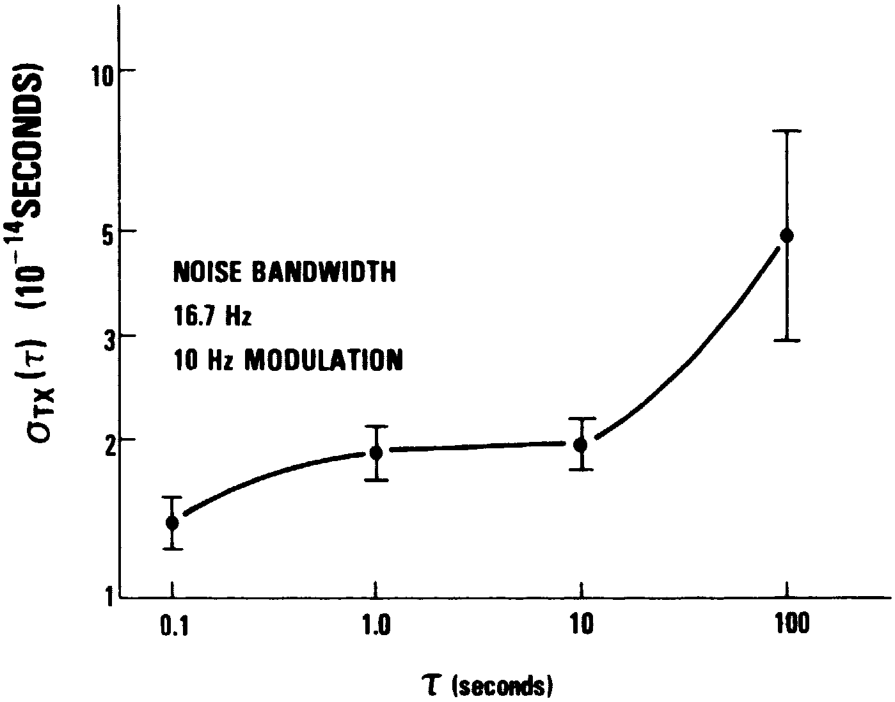


Fig. 11–5MHz Phase Resolution with Time Interval Counter

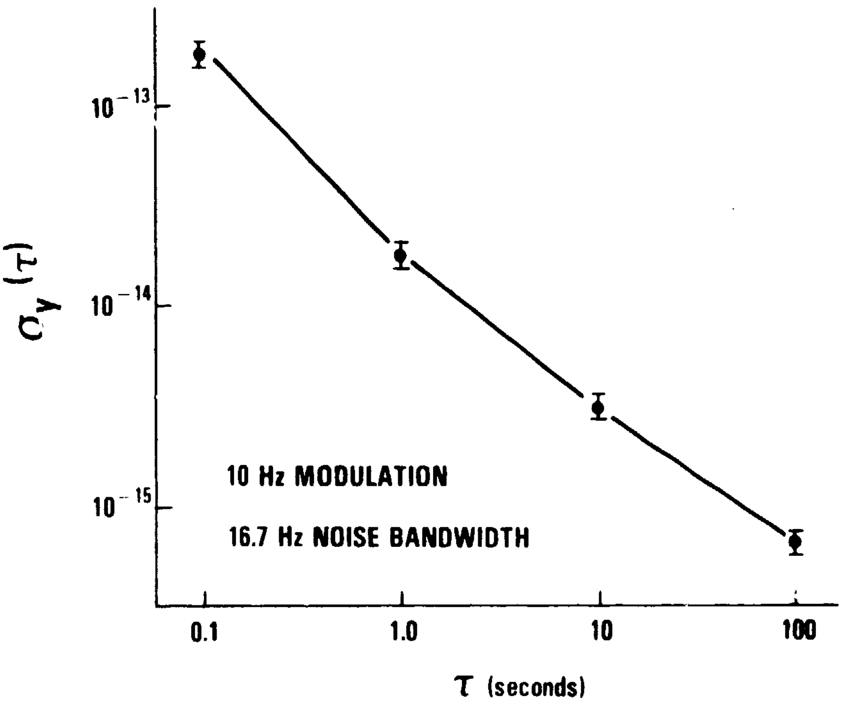


Fig. 12–5MHz Phase Resolution with Period Counter